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A Vision For A Beach Forecasting Tool

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Summary

The societal value of safe access to swimmable water is intuitive and in many countries it is a legal right. Threats to water quality reduce these recreational opportunities. The risk comes from exposure to waterborne pathogens from a myriad of sources, both human and animal. Different aspects of this public health issue are addressed in detail by public and private organizations. However, except for monitoring and general guidelines, the public has little access to scientific prognoses on the impending conditions of bathing waters. This paper describes work to combine the efforts of several organizations to produce software designed to assist public health officials and the public in general in assessing the likely short-term quality of the nation's local beaches.

Keywords:

Beaches, Visual Beach, pathogens, bacteria, discharge, software, models, swimmable water

Introduction

The appeal of beaches is well illustrated by a photo that appeared in the Peruvian daily newspaper El Comercio (Fig. 1) [1,2]. The Peruvian beach and a Great Lakes Beach on a quiet late-spring week day (Fig. 2) contrast with a beach warning sign (Fig. 3). Beach closures due to water quality that exceeds standard limits occur frequently in the United States [3]. Closures deprive the public of opportunities for recreational activities and can have a significant impact on local economics. These undesirable conditions heighten interest in potential approaches to keeping beach closures to a minimum, maintaining safe waters for recreational swimming.

Many studies show that current monitoring approaches for assessing water quality do not fully protect public health [4,5,6]. The reason is simple. Standard monitoring methods take 24 to 48 hours to complete [7] so that decisions to close beaches are frequently made after the fact without knowledge of actual current conditions. As a result, beaches may be closed when conditions have returned to safe levels and others remain open when conditions are hazardous.

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Figure 1. Playa Costa Verde, Peru. An example of an open beach and a graphic expression of the importance of beach resources. [1,2]

Figure 2. Morning,West Beach, Lake Michigan, Indiana, June 2003. Note Chicago skyline. Photo, W. Frick

Working separately, the United States Environmental Protection Agency (USEPA) and the United States Geological Survey (USGS) have been actively engaged in developing prognostic and diagnostic tools to effectively determine when unacceptable water quality will occur [8,9].

Until now, their programs have not been integrated, nor has related work of other organizations been included. The USEPA, USGS, and the National Oceanic Atmospheric Administration (NOAA), and other federal and local agencies are supporting and developing scientific programs and models that are logical components of an integrated effort to predict bacteria concentrations on beaches. This work describes a joint effort to develop the Beach Forecasting Tool (BFT).

Figure 3. A beach water quality advisory

1. Legislative Background

Recently the U.S. Congress passed the Beaches Environmental Assessment and Coastal Health Act of 2000. Under Section 2 of the Law, it states that "each State having coastal recreation waters shall adopt and submit to the [USEPA] Administrator water quality criteria and standards for the coastal recreation waters of the State for those pathogens and pathogen indicators for which the Administrator has published criteria under section 304(a)." And, "not later than 36 months after the date of publication by the Administrator of new or revised water quality criteria under section 304(a)(9), each State having coastal recreation waters shall adopt and submit to the Administrator new or revised water quality standards for the coastal recreation waters of the State for all pathogens and pathogen indicators to which the new or revised water quality criteria are applicable."

Under Section 3 of the Law, Revisions to Water Quality Criteria, (a) Studies Concerning Pathogen Indicators in Coastal Recreation Waters, it states that Section 104 of the Federal Water Pollution Control Act (33 U.S.C. 1254) is amended by adding at the end the following:

> ''(v) STUDIES CONCERNING PATHOGEN INDICATORS IN COASTAL RECREATION WATERS.— Not later than 18 months after the date of the enactment of this subsection, after consultation and in cooperation with appropriate Federal, State, tribal, and local officials (including local health officials), the Administrator shall initiate, and, not later than 3 years after the date of the enactment of this subsection, shall complete, in cooperation with the heads of other Federal agencies, studies to provide additional information for use in developing—
>
> ''(1) an assessment of potential human health risks resulting from exposure to pathogens in coastal recreation waters, including nongastrointestinal effects;
>
> ''(2) appropriate and effective indicators for improving detection in a timely manner in coastal recreation waters of the presence of pathogens that are harmful to human health;
>
> ''(3) appropriate, accurate, expeditious, and cost-effective methods **(including predictive models)** for detecting in a timely manner in coastal recreation waters the presence of pathogens that are harmful to human health; and…."

The text in bold, added for emphasis, served as the incentive for the work described here. In March 2004, a cross-agency group including USEPA, NOAA, and the USGS met to formulate a plan to develop computer models to assist State and local authorities and other interested parties to estimate beach bacteria concentrations. The ultimate goal is to issue forecasts similar to those disseminated by weather services.

2. Rationale

The concept of the BFT is simple: combine data on bacteria sources, stresses, bathymetry, atmospheric conditions, and aquatic conditions with statistical and hydrodynamic models to produce three-day forecasts of beach concentrations. BFT is at the core of the model called Visual Beach. It is envisioned that Visual Beach forecasts would be available to the general public on the internet and disseminated to registered users, including the media, thus allowing the public to better plan their recreational time. Monitoring results would be used to set initial conditions for Visual Beach and provide verification data, while Visual Beach forecasts would overcome the temporal lag in monitoring and could help guide or modify monitoring schedules and design.

A tiered approach is envisioned to accommodate users, with relatively accessible empirical models intended for small municipalities and data sparse areas, to more sophisticated and data intensive models for major water bodies and heavily populated regions. For example, an empirical model may relate rainfall events to beach bacteria concentrations to generate short-term forecasts of beach conditions. On the other hand, major urban public agencies may use specifically tailored numerical circulation and bacterial decay models (as presently found in Visual Plumes [9]) to predict movement of water and the physical stresses on bacteria and pathogens to produce specific forecasts of bacteria dispersion and survival.

An important incentive for developing BFT is that the partnering organizations have developed the important components in recent years. To use the Great Lakes beaches as an example, NOAA has developed a circulation model for Lake Michigan, example output is shown in Fig. 4 [10]. Point source models have been developed by USEPA, including Visual Plumes [9] which also serves as a concept prototype and resource for Visual Beach. These models could be coupled, the general circulation model providing hydro-dynamical boundary conditions for the Visual Plumes near-field model. Alternatively, an integrated model might couple near-field and far-field models. Empirical modelling methodologies have been developed by USGS for Lake Erie and other regional beaches [6,8]. USEPA and USGS microbiologists and epidemiologists have compiled data and developed source strength and mortality models to enable initial bacterial concentrations and decay rates to be estimated [9,11,12].

The goal is to develop and demonstrate a BFT prototype in 2005 that will include modules to help define the site(s), satellite images, maps, weather maps, internet linkage, etc.; tools to describe and assess current conditions, e.g., bacterial decay calculators; one or more empirical models for application to data sparse sites; and an implementation of integrated source, circulation, and bacterial fate models.

3. Visual Beach Interface Prototype

In addition to the models and model integration, the Visual Beach interface will be critical to the overall success of the concept. This interface has yet to be created. However, even a prototype interface is valuable, helping to shape the perceptions, hopes, and expectations of principal investigators, post doctoral candidates, and potential collaborators alike. A prototype interface has been developed that adapts the Visual Plumes interface [9], used here to illustrate some of the themes for, and challenges of, developing the Visual Beach interface.

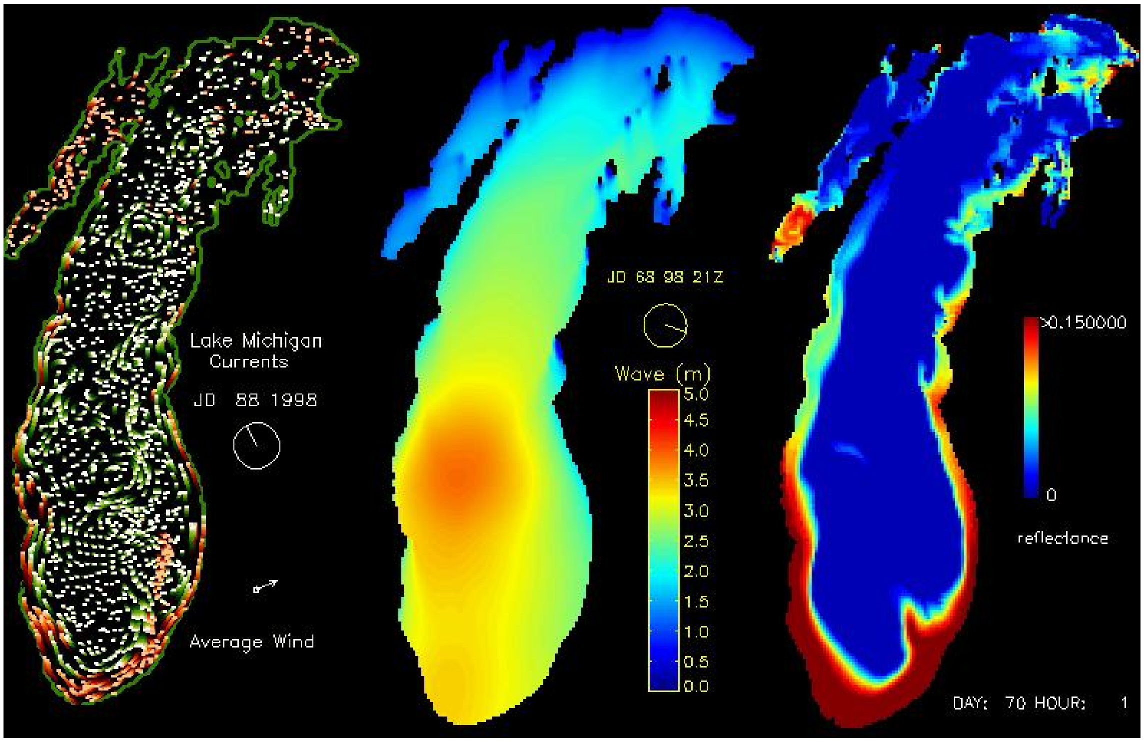


Figure 4. NOAA Lake Michigan circulation model output; left to right, particle trajectories, wave height, and sediment reflectance.

Some of the basic requirements of the interface include a web-served environment (for example, as provided by the Visual Component Language found in the Delphi integrated development environment [13]), coding in object-oriented programming, and internet programming. It is difficult to predict the ultimate appearance and functionality of the Visual Beach interface, but organizational features and user facilities will play important roles in determining the success of the application. Organization can be achieved by the use of tabs, inheritance, polymorphism, context sensitive branching, and other constructs [13]. Functionality and intuitiveness can be enhanced by the use of modern visual components: buttons, lists, radio control panels, dialog boxes, and so forth. Downloading, database handling, program setup and execution are among other functions to be developed. The automatic sharing of information between different objects will be facilitated by object-oriented programming and should be uniformly and universally implemented.

A tabular structure, for example, provides a candidate organizational structure that puts entry level and basic constructs at the forefront, including data gathering and visualization activities. These tabs will be designed to help users acquire the information to complete the contextual setting in which the beach bacteria prediction problem exists. This includes geographical information, satellite images, monitoring information, contact information, regulations, and so forth. The entry-level tab for the Visual Beach straw interface is shown in Fig. 5.

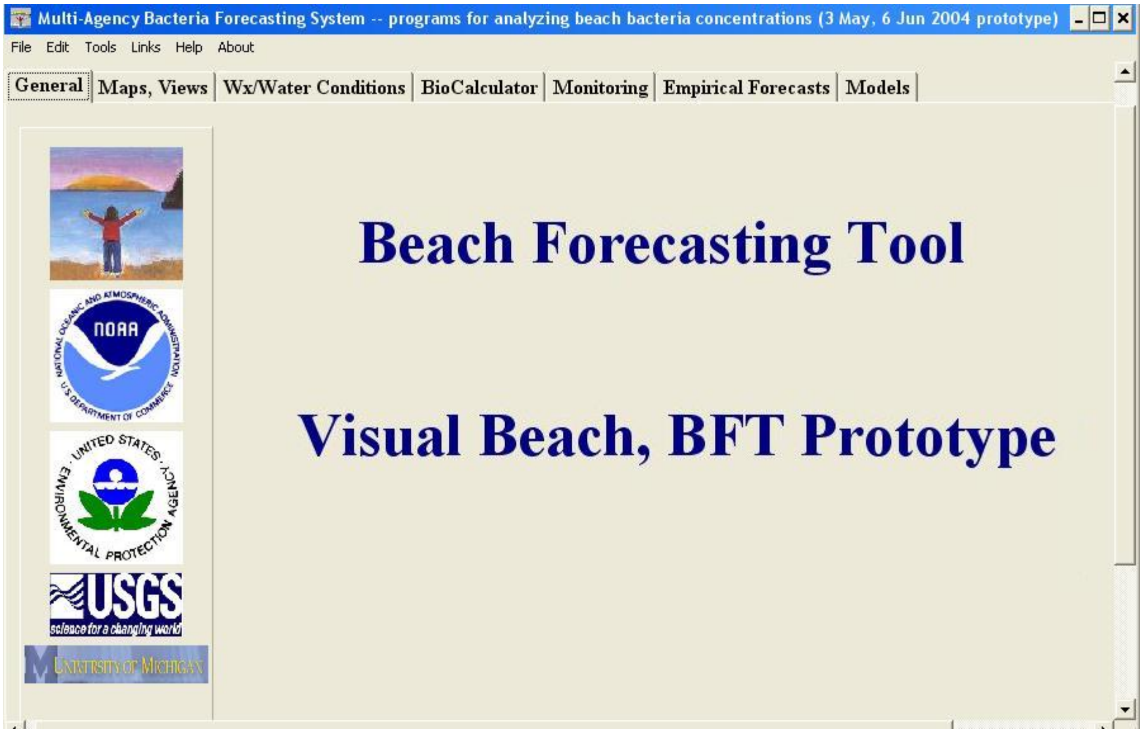


Figure 5. Visual Beach prototype entry-level tab.

At a deeper level (tabs) are interpretive tools, including spreadsheets and calculators, for example, the BioCalculator tab in Fig. 5. The Monitoring tab will house information that will help users develop, conduct, maintain, and interpret monitoring data and information. Polymerase Chain Reaction (PCR) modules are envisioned for both tabs [14]. The Empirical Forecast tab, as further described in the next section, will include statistical and empirical models that are readily accessible to individuals and small groups with limited resources. Finally, the models tab is envisioned to provide access to sophisticated models and programs, as for example, linked near-field and far-field models [15]. These sophisticated tools are intended for large municipalities, parks, and recreation areas. For example, in the extant prototype, the Visual Beach models tab allows the user to setup and run the USEPA Visual Plumes models [9].

To show feasibility of concept, a simple bio-calculator has been written for Visual Beach, Fig. 6. Based on the Mancini coliform model [16], it calculates the T-90 time, the time for 90% of the organisms to die off under the specified conditions. As can be seen the inputs are fairly technical, requiring solar insolation (sunlight intensity) and turbidity for example. However, tab cross-linking would alleviate the data burden on the user. Thus information acquired on the maps and weather tabs, for example, cloud cover, latitude, time of year, and the like, would be used to provide estimates for these values, that the user could override if desired.

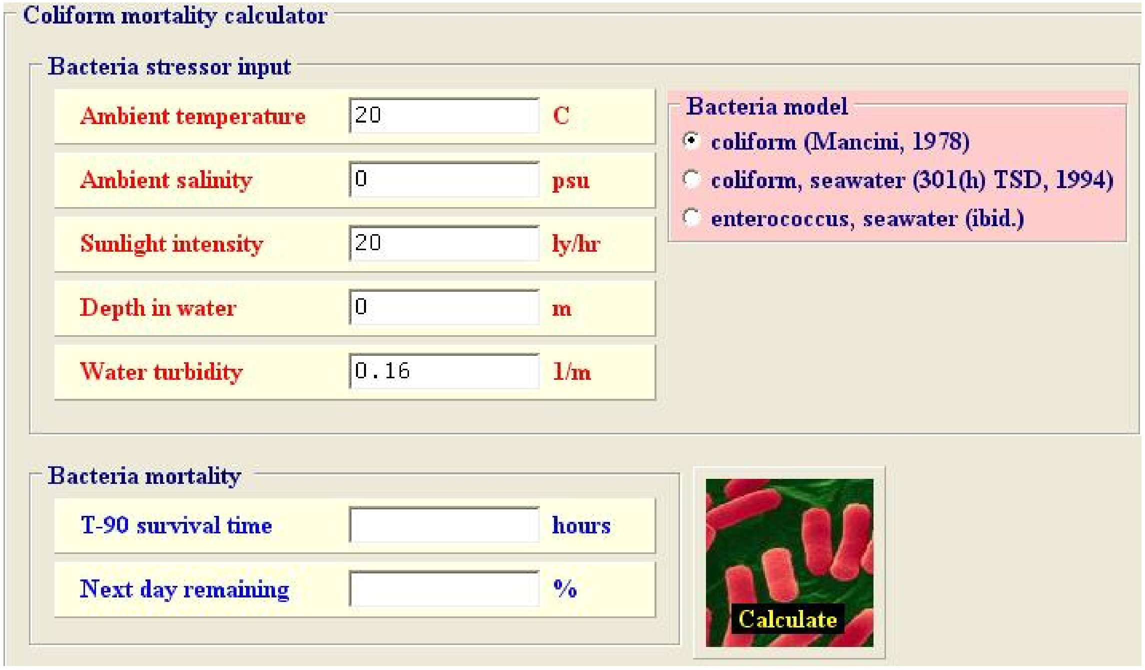


Figure 6. Prototype Visual Beach bacterial mortality “Bio-calculator”.

4. Empirical Models

For maximum benefit, Visual Beach should be useful to individuals and small offices with limited resources. The tiered approach is designed to address that challenge. Most offices will not have the luxury of applying the hydrodynamical models envisioned for Visual Beach. For them, Visual Beach will offer statistical and empirical models that may be applied without the effort that is for most infeasible. These methods will rely on a modicum of data availability and relatively simple statistical or empirical models with limited input.
Such methods are currently in use and development of the USGS and are used to predict beach conditions at several locations in the Midwestern United States. One was developed for Huntington, Bay Village, Ohio in a study in cooperation with the Cuyahoga County Board of Health and the Cuyahoga County Sanitary Engineers [8]. The basic steps in this methodology are:

(1) Determining correlation coefficients calculated on the strength of the association between *E. coli* and a number of continuous variables measured during the study, for example, antecedent rainfall, water temperature, flow, turbidity, wave height, solar radiation, and bird counts, among others.
(2) Plotting the data to provide additional information on the relations between *E. coli* and other variables. The results are checked for outliers or data points that strongly influence the relations.
(3) Summarizing and tabulating the correlations to facilitate the process of selecting variables to include in the model development step.
(4) Creating box plots to help understand the distribution of *E. coli* concentrations in variables that are not continuous, but, rather, are grouped by categories, such as wave

height and current direction.

(5) Preparing and using analyses of variance (ANOVA) to determine the relations between categorical variables and *E. coli* concentrations. The Tukey-Kramer multiple-variable comparison test is used to determine which groups differ from each other and the results are categorized, as by letters (ABCD). These tests help to identify the important variables and provide insights for grouping categorical data for model development.

(6) Identifying the important variables to be used to generate a list of possible models using Mallow's Cp test. Model comparison then identifies the most promising models. Models are checked for related variables (for example, multiple rainfall variables), for too many variables, and for impractical combinations. This is a somewhat subjective process, aided with Cp and R^2 statistics.

(7) Scrutinizing the most promising models and model variables once more for potential weaknesses. The variables are checked for significance and the partial plots of residuals are evaluated.

(8) Selecting the most promising models, sometimes, if possible, in consultation with experts in regression analysis.

Example raw data with weak and strong correlations used for exploratory data analysis are illustrated and compared in Fig. 7. A draft table with correlation coefficients and box plots of categorical data are shown in Fig. 8. Finally, notes of model statistics and a plot of residuals, used in model evaluation and selection, are shown in Fig. 9. These examples are illustrative of the methodology, the data being unimportant. One of the first challenges for the Visual Beach developers is to write the code that will facilitate performing such analyses, providing spread sheet, graphics, and other support.

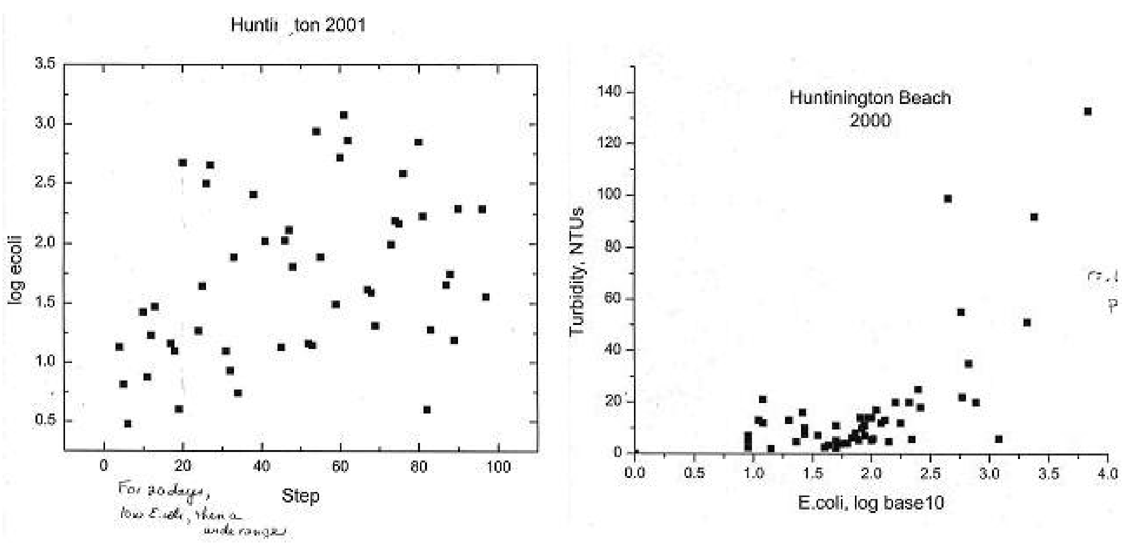
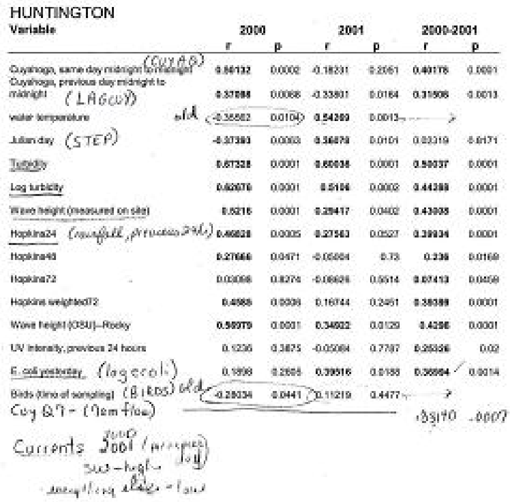


Figure 7. Preliminary plots comparing raw data with weak and strong correlations.



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Variable	2000 r	2000 p	2001 r	2001 p	2000-2001 r	2000-2001 p
Cuyahoga, same day midnight to midnight (CUYAQ)	0.56132	0.0002	-0.18231	0.2061	0.40176	0.0001
Cuyahoga, previous day midnight to midnight (LAGCUY)	0.37088	0.0068	-0.33801	0.0164	0.31506	0.0013
water temperature old	-0.35502	0.0104	0.54209	0.0013		
Julian day (STEP)	-0.37393	0.0003	0.36879	0.0101	0.03319	0.0171
Turbidity	0.67328	0.0001	0.60036	0.0001	0.50037	0.0001
Log turbidity	0.62076	0.0001	0.5106	0.0002	0.44288	0.0001
Wave height (measured on site)	0.5216	0.0001	0.29417	0.0402	0.43008	0.0001
Hopkins24 (rainfall, previous 24hr)	0.46628	0.0005	0.27563	0.0527	0.39934	0.0001
Hopkins48	0.27666	0.0471	-0.05004	0.73	0.236	0.0168
Hopkins72	0.03096	0.8274	-0.08626	0.5514	0.07413	0.0459
Hopkins weighted72	0.4585	0.0006	0.16744	0.2451	0.38389	0.0001
Wave height (OSU)--Rocky	0.58979	0.0001	0.34622	0.0129	0.4296	0.0001
UV intensity, previous 24 hours	0.1236	0.3875	-0.05084	0.7787	0.25326	0.02
E. coli yesterday (logecoli)	0.1898	0.2605	0.39516	0.0188	0.36664	0.0014
Birds (time of sampling) (BIRDS) old	-0.28034	0.0441	0.11219	0.4477		
Cuy Q7 - (9am flow)					.33170	.0007

Currents 2000 2001 (averaged day)
sw - high
everything else = low

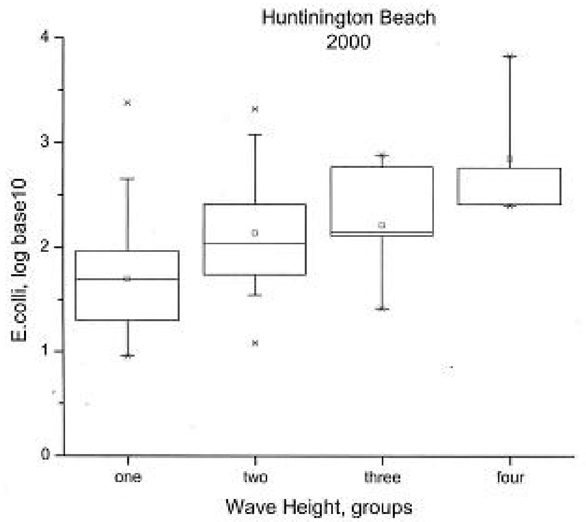
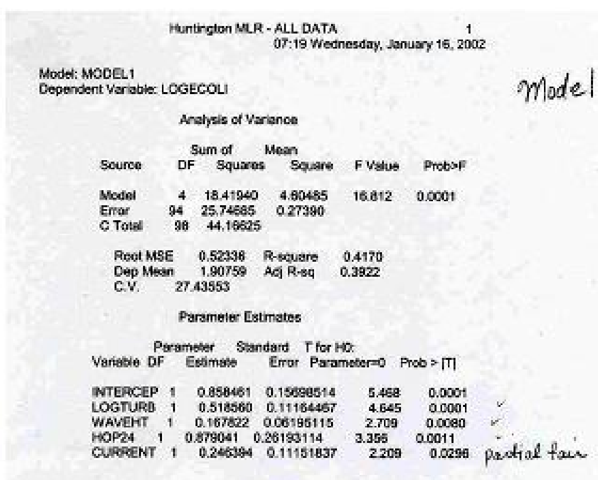


Figure 8. Draft table and research notes of correlation coefficients and an example box plot.



Huntington MLR - ALL DATA 1
07:19 Wednesday, January 16, 2002

Model: MODEL1
Dependent Variable: LOGECOLI

Model 1

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	4	18.41940	4.60485	16.812	0.0001
Error	94	25.74685	0.27390		
C Total	98	44.16625			

Root MSE	0.52336	R-square	0.4170
Dep Mean	1.90759	Adj R-sq	0.3922
C.V.	27.43553		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	T for H0: Parameter=0	Prob > |T|
INTERCEP	1	0.858461	0.15698514	5.468	0.0001
LOGTURB	1	0.518560	0.11164467	4.645	0.0001
WAVEHT	1	0.167822	0.06195115	2.709	0.0080
HOP24	1	0.879041	0.26193114	3.356	0.0011
CURRENT	1	0.246394	0.11151837	2.209	0.0296

partial four

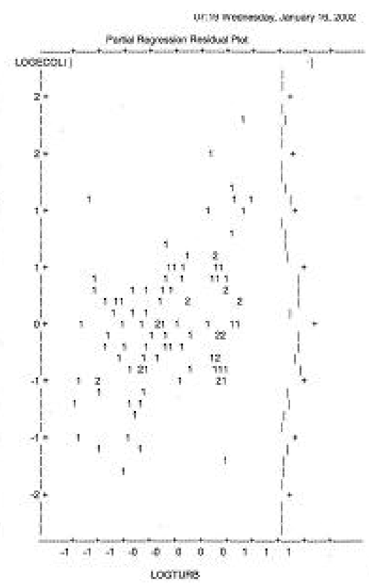


Figure 9. Research notes and model statistics and partial plots of residuals.

5. Visual Beach Potential in the Great Lakes Region

Dependence on analytical procedures on Great Lakes beaches are too slow to advise beach managers on when to close, keep open, or reopen a beach. Computer models are needed to now-cast and forecast *E. coli* levels in southern Lake Michigan, linked to web sites, to provide monitoring and modeling results at beaches so that the swimming community can plan their weekend.

Potential interstate impacts are incentive for the states to foster the development of better diagnostic and prognostic forecasting tools, such as Visual Beach, The hypothesized effect of Milwaukee storm discharges on beach closings in Chicago serves as an example.

Projects supported by the Great Lakes National Program Office to reduce dependence on current bacterial analytical procedures include the following:

(1) The USGS to field test and statistically compare a new rapid *E. coli* measurement protocol tests using flow cytometry, a new technology based on laser detection of bacteria with current cultural test bacteria measurement technology. A rapid test protocol can provide same day evaluation of bacteria counts allowing for better decisions concerning beach posting decision.

(2) The Department of Environment, City of Chicago for a multi-beach mapping and modeling of *E. coli* to develop a predictive model that uses wind direction, wind velocity, rainfall, sources of contamination, turbidity, antecedent *E. coli* concentration, water depth, beach morphology, and the orientation of beaches to lake, air and water temperature for southern Lake Michigan. This effort was expanded to southeast Wisconsin to Gary, Indiana. This forecast program can provide rapid information similar to weather forecasting and reduces the dependence on individual beach monitoring programs.

(3) The Great Lake Commission to develop web pages for public beaches showing beach locations and characteristics; responsible agencies for management; key contacts for water quality monitoring and reporting; monitoring and assessment standards, advisory authority criteria and reporting; closure frequencies; closure and re-opening protocols; history and causes (when known) of a closure or restriction; and information on any current closure or restriction. The site also may include features such as a bulletin board for information sharing, model standards, monitoring assessment and advisory criteria, and related items to enhance human health protection. This service will be incorporated into the U.S. USEPA national BEACH program database and widely accessible through the Great Lakes Commission-led Great Lakes Information Network.

Figures 10 and 11 link land satellite images of Lake Michigan on May 25th and June 3rd to the same days of a simulation of the Milwaukee River plume coming from Milwaukee Wisconsin as modelled by the hydrodynamic lab, Center for Great Lakes and Human Health at GLERL, NOAA. These simulations illustrate how Visual Beach would be linked to land satellite images and hydrodynamic plume forecasting based on wind direction and other meteorological information. Figure 10 shows a sediment river plume south of Milwaukee on 25 May moving southeastward into Lake Michigan. By 3 June, the feature has subsided. Figure 11 shows a simulation of the river plume, illustrating how such a model accessed by or implemented in Visual Beach would be able to predict movement plumes in ambient waters.

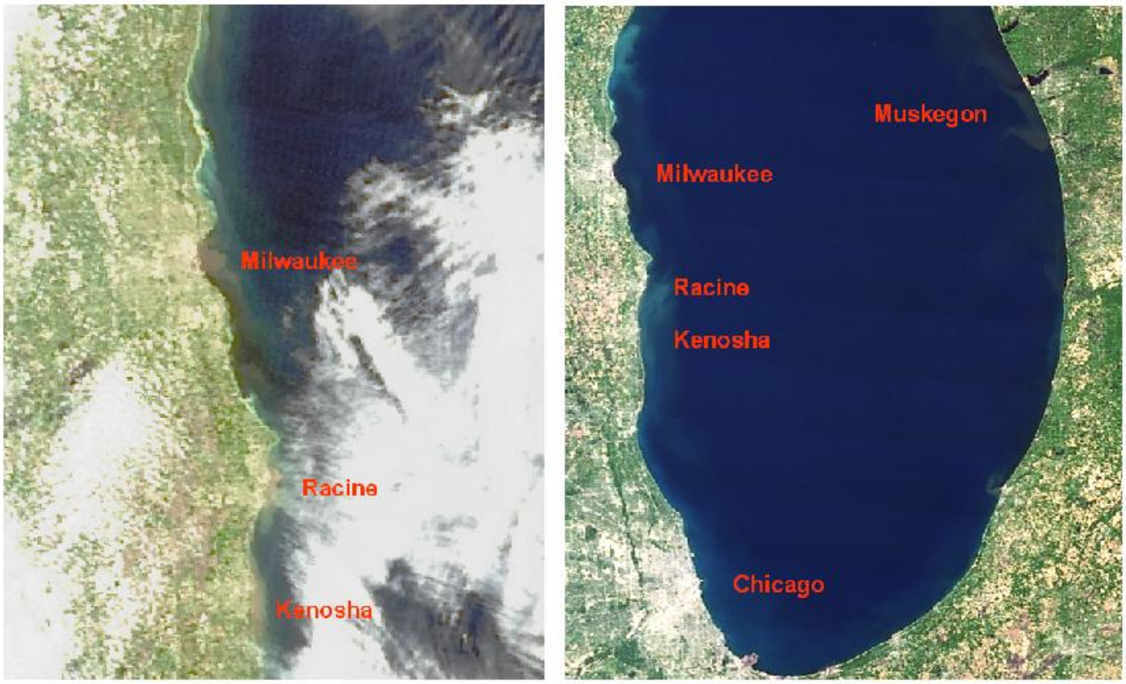


Figure 10. Left, a river sediment plume is visible from space south of Milwaukee, 25 May 2004. Right, southern Lake Michigan, 3 June 2004, the plume has largely dissipated.

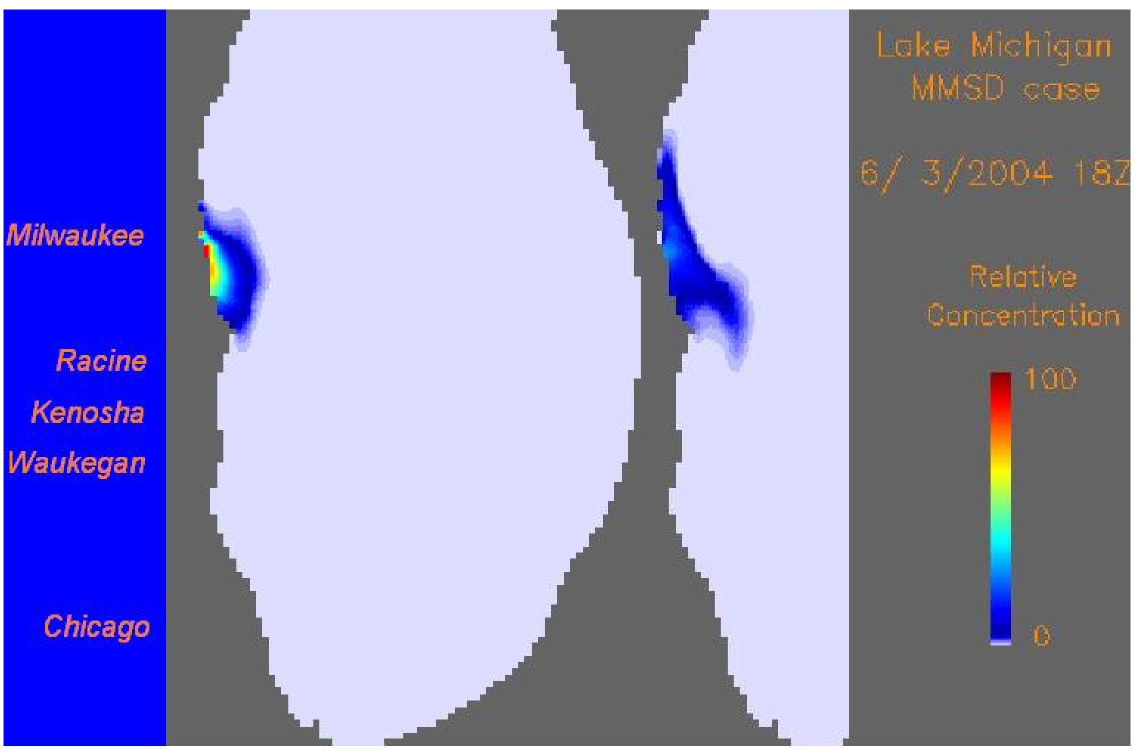


Figure 11. NOAA plume simulation, May, June 2004. Note, the color CD version of this paper best shows relative concentrations and other graphics features.

Conclusion

Access to safe, swimmable water is important to millions of Americans. Multiple governmental and academic organizations possessing pertinent scientific tools are joining forces to help local health officials to simulate and predict beach bacteria concentrations. Visual Beach is a prototype of a Beach Forecasting Tool that is under development to integrate models to make them accessible to public health officials and other interested parties to predict beach conditions and, ultimately, help reduce beach closures.

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